Hysteresis Modeling and Compensation

Experience from SPS and prospects for other machines

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EPA WP4
BE-CSS-DSB | TE-MSC-TM (→ MMM)

Outline

- Hysteresis in accelerator magnets and impact on operations
- Feed-forward hysteresis compensation (with artificial intelligence)
  - Significant achievements
  - … and challenges encountered

  - Magnetic modeling
  - Controls integration
  - Guardrails and monitoring
  - Magnetic measurement lessons and improvements
- Operational status of hysteresis compensation
- Outlook and conclusion

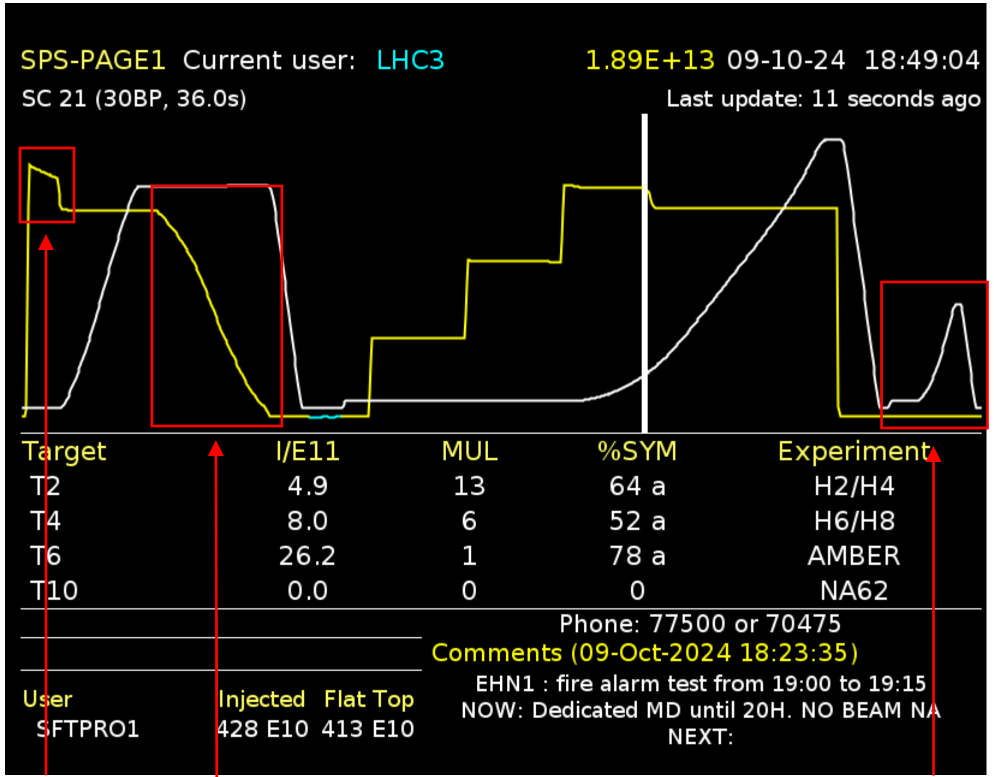
Hysteresis in the accelerator magnets

And the need for reproducible fields

- Nonlinear static and dynamic effects in accelerator magnets, when uncorrected …
  - … hinder the efficiency and flexibility of (multi-cycling) accelerator operations

! N.B. Only PSB and PS dipoles have feed-back field control

- SPS status quo
  - MD1 quasi-degaussing cycle
  - Manual change of SFT beam tune whenever LHC requests beam
  - Still beam losses / degradation at injection
- Other accelerators
  - Degaussing cycles and constrained cycle sequences due to hysteresis



Injection losses
- Eddy current decay
- Hysteresis

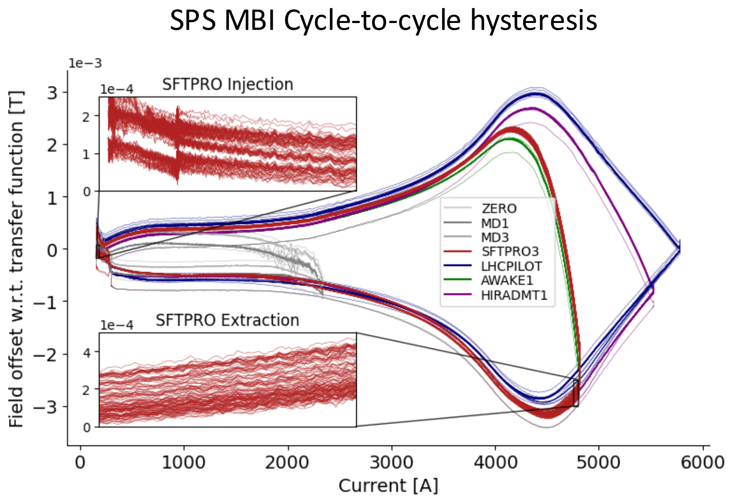
(Extracted) beam quality degradation
- Changing spill macrostructure

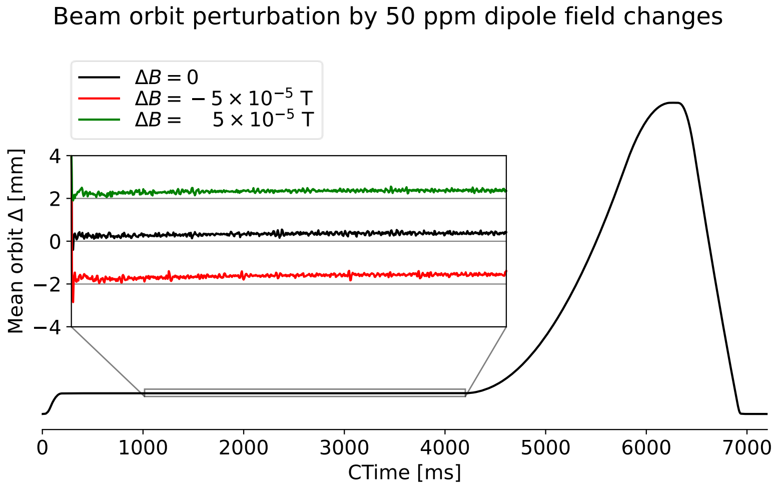
Waste of energy
- 5 kWh every cycle
- … for quasi-degauss
- … and for reproducible eddy currents

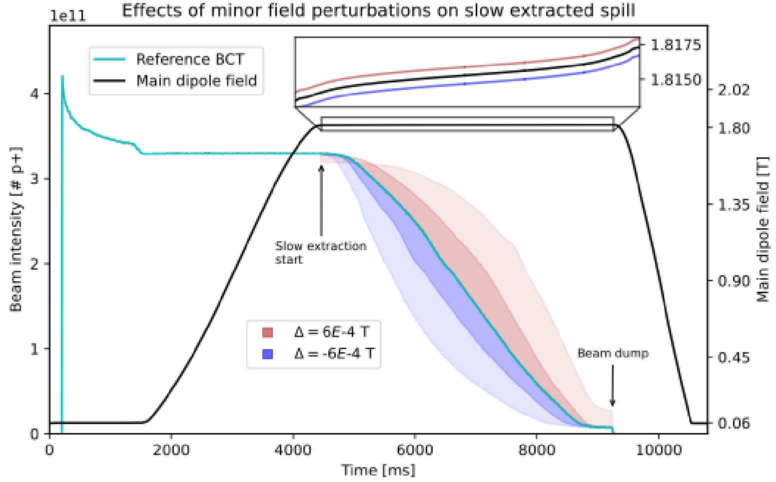
Hysteresis in the accelerator magnets

And the need for reproducible fields

- Cycle-to-cycle differences are small …
  - Hysteresis effects ± 1 permil, but cycle-to-cycle differences are $\pm$ 100 ppm or less … (in SPS MBIs)
- … But still significant effects on beam
  - 100 ppm tolerance on SFT 400 GeV flat top
  - 10 ppm tolerance on 14 or 26 GeV flat bottom



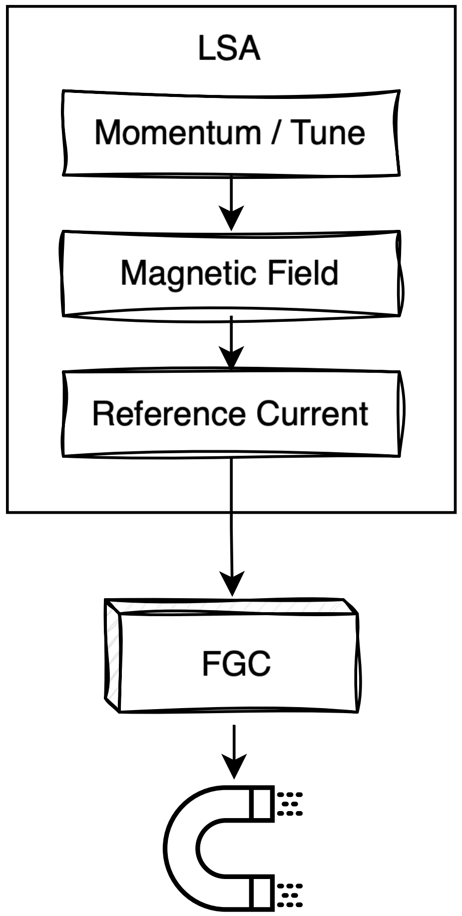




What if we could have reproducible fields…

Through feed-forward field compensation

- Most magnetic circuits are controlled in current by translating momentum / tune / correction etc.



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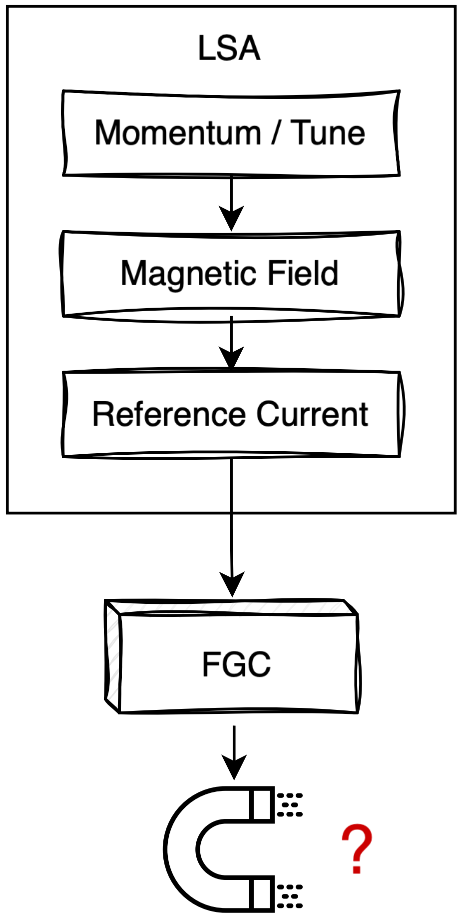

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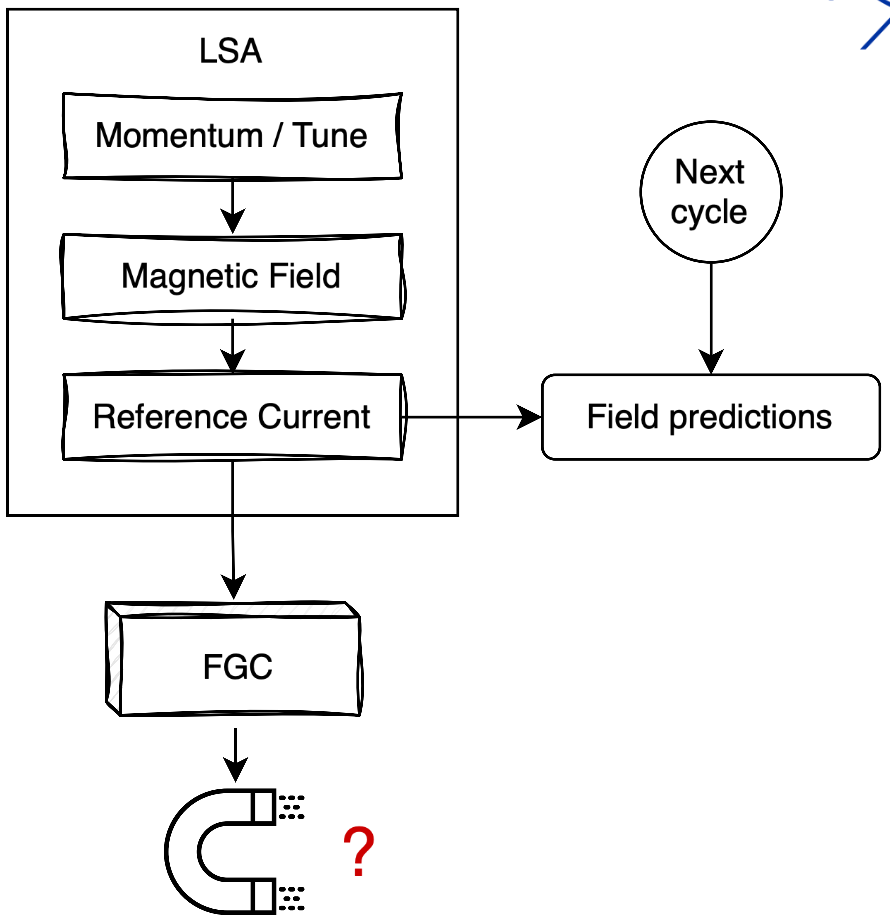

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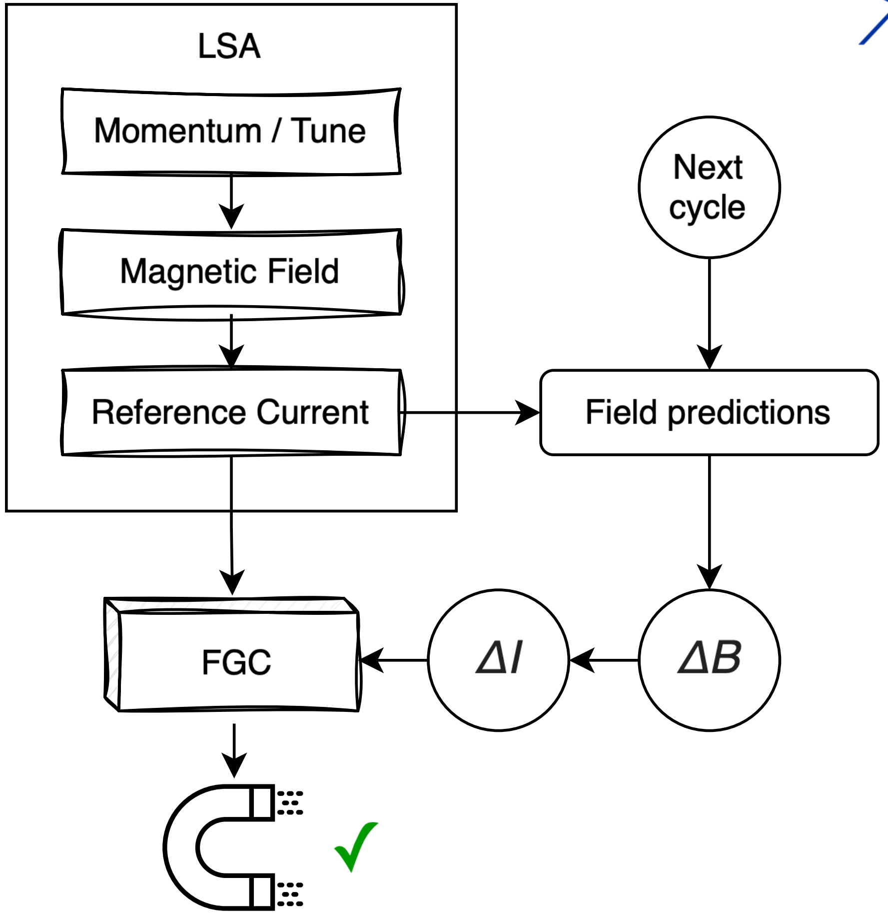
  - … feed-forward correct the field by applying a ΔI



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Through feed-forward field compensation

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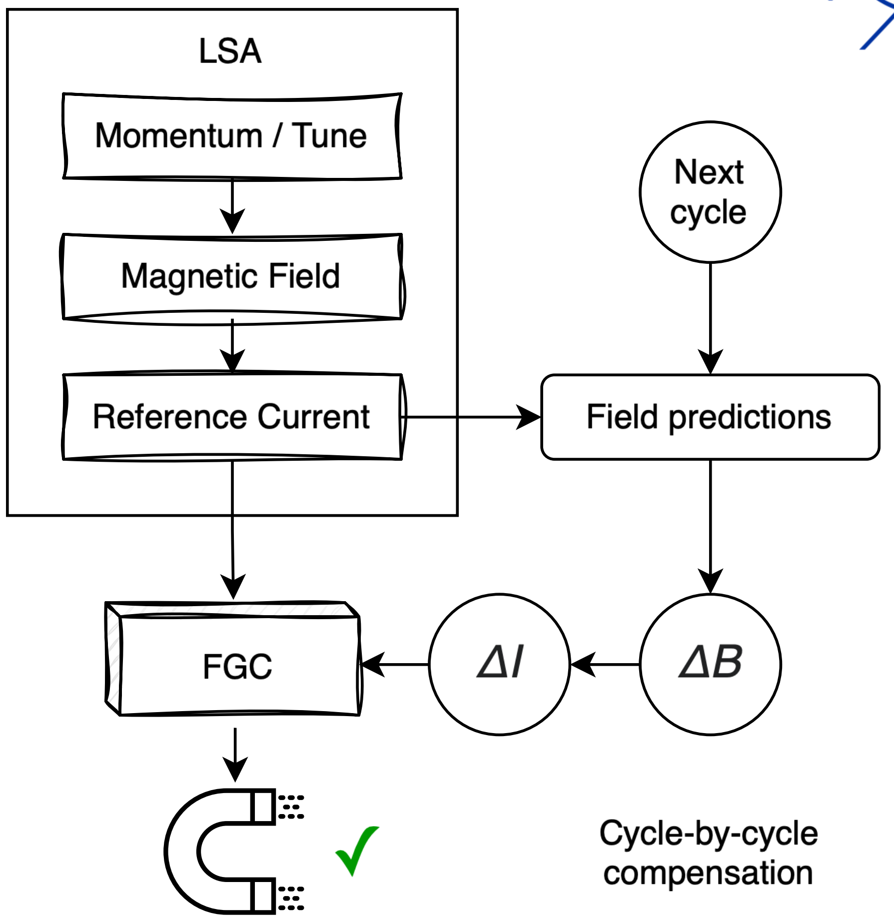
  - Control system is agnostic to actual field response in the machine

- Instead: model magnetic field response $I \rightarrow B$ with ML, from measurements
  - Knowing next cycle to be played …
  - … feed-forward correct the field by applying a ΔI for every cycle
  - ⇒ We now can achieve reproducible fields
  - Control paradigm is transparent to set B / Q / K

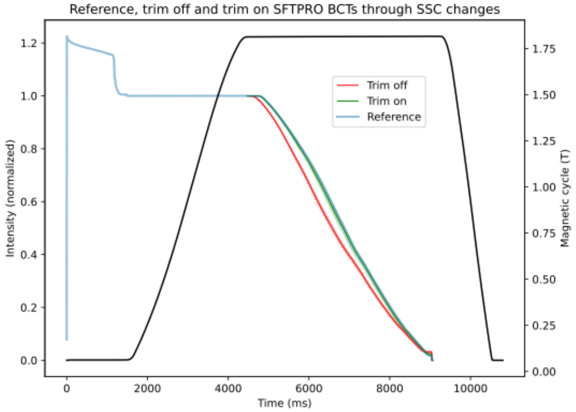


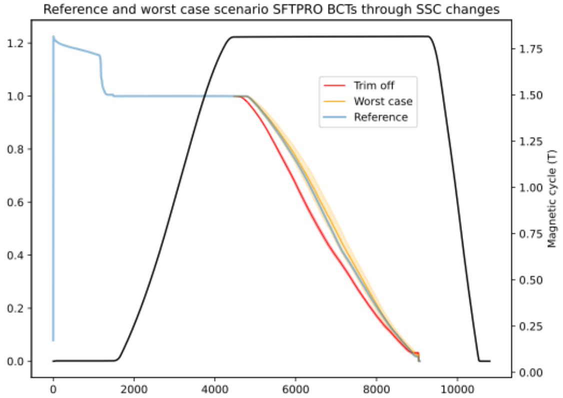
❗ N.B. Assume that all effects can be modeled by measuring field

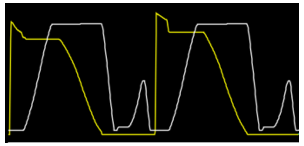
Significant achievements in 2024

Operations-ready field compensation

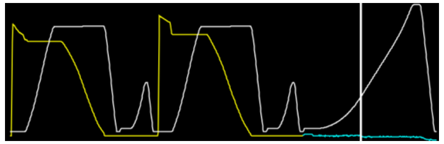
- Successful SPS MB compensation on SFT flat top
  - For common physics configurations, during MDs
    - Spill macrostructure stable for over 1h
  - Field compensation around $100\ \mathrm{ppm}$ ($2\text{-}3 \times 10^{-4}$ T $\Rightarrow \Delta I \approx 0.7$ A)
  - Main operational study thus far only MBIs…
  - … but other SPS magnetic circuits coming soon
- Field prediction and compensation at injection
  - Low field predictions challenging ($\Delta B \approx 10\ \mathrm{ppm}$ required), where beam rigidity is low, but possible
  - Not all effects on the beam can be seen on measured field
- Flexible and modular modeling and feed-forward compensation strategy in place
  - Compatible with other magnetic circuits







(Field compensation OFF)
FT + LHC → 2x FT

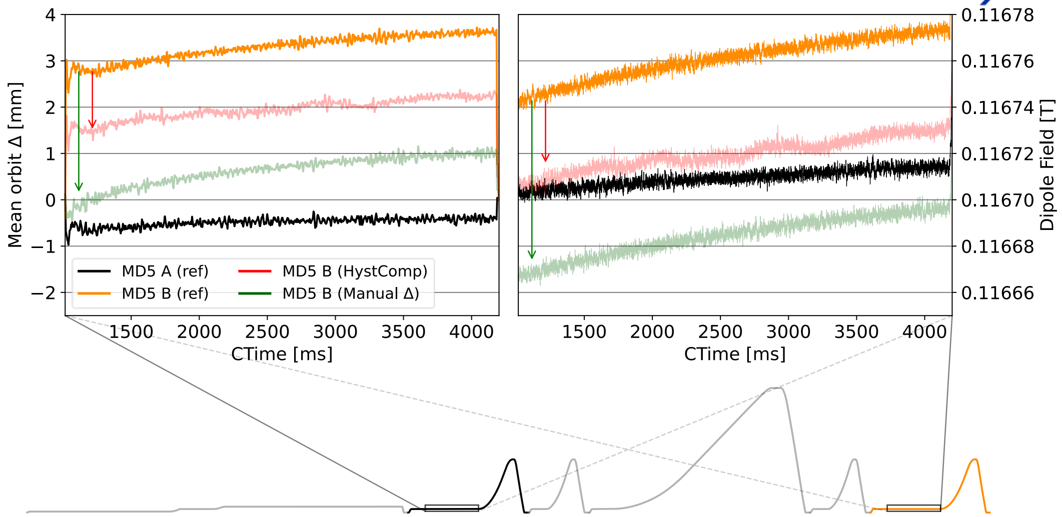


Field compensation ON – worst case

Significant achievements in 2024

… and challenges

- Only effects from measured field can be compensated by field prediction
  - Field predictions satisfy the required accuracy $10\ \mathrm{ppm}$
  - But some (dynamic) effects on beam still not explained
  - … and highly accurate field predictions, (and hence compensation) are difficult to achieve for 100 % of scenarios



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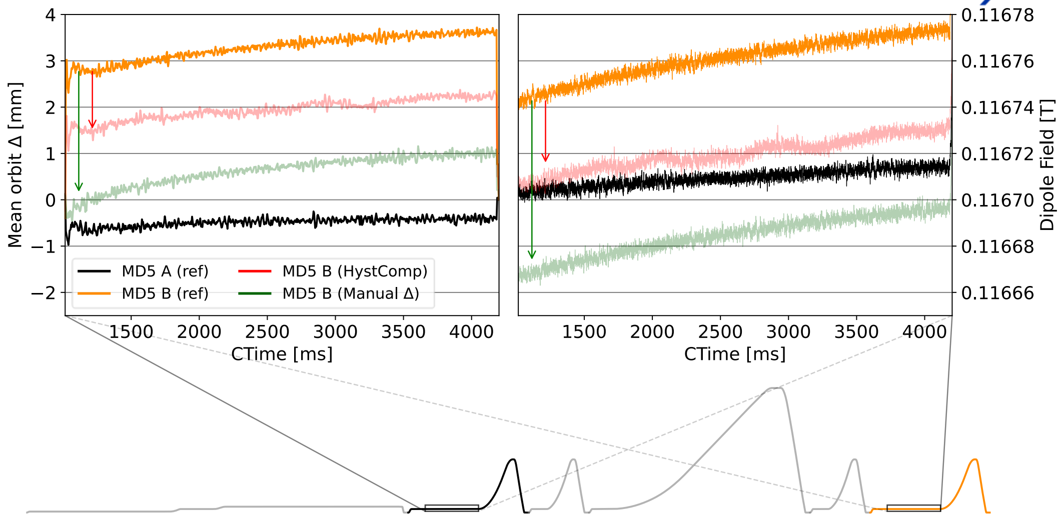
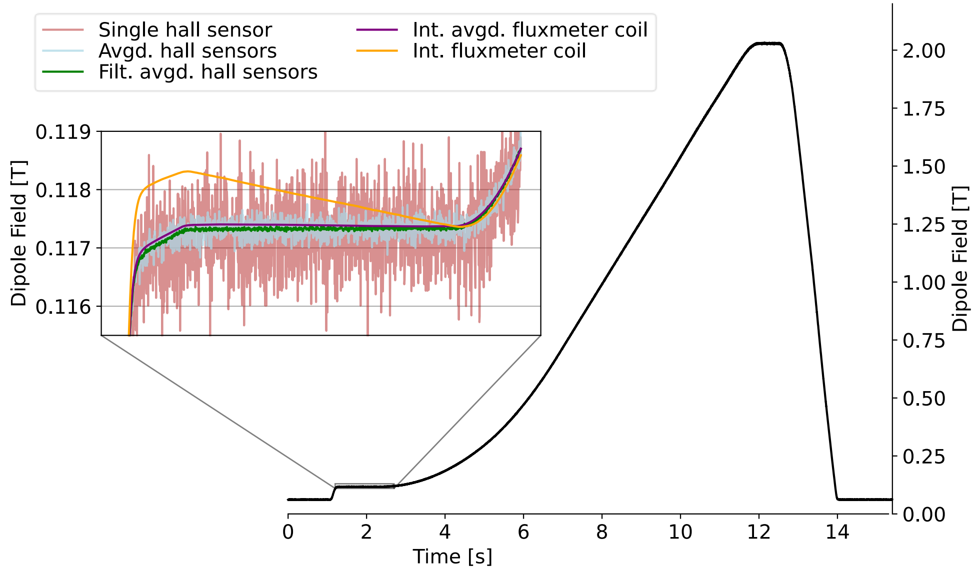


- High-accuracy pulsed lab measurements are extremely challenging
  - Pulsed field measurements in lab remain limited at $\approx 100\ \mathrm{ppm}$
  - … compared to online B-Train at $\approx 10\ \mathrm{ppm}$
  - Significant work required to achieve desired accuracy



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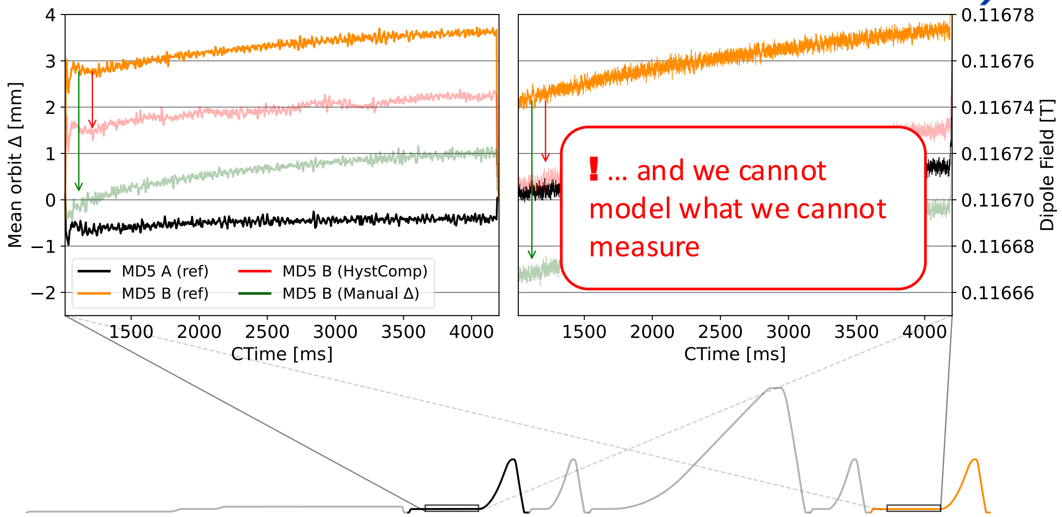

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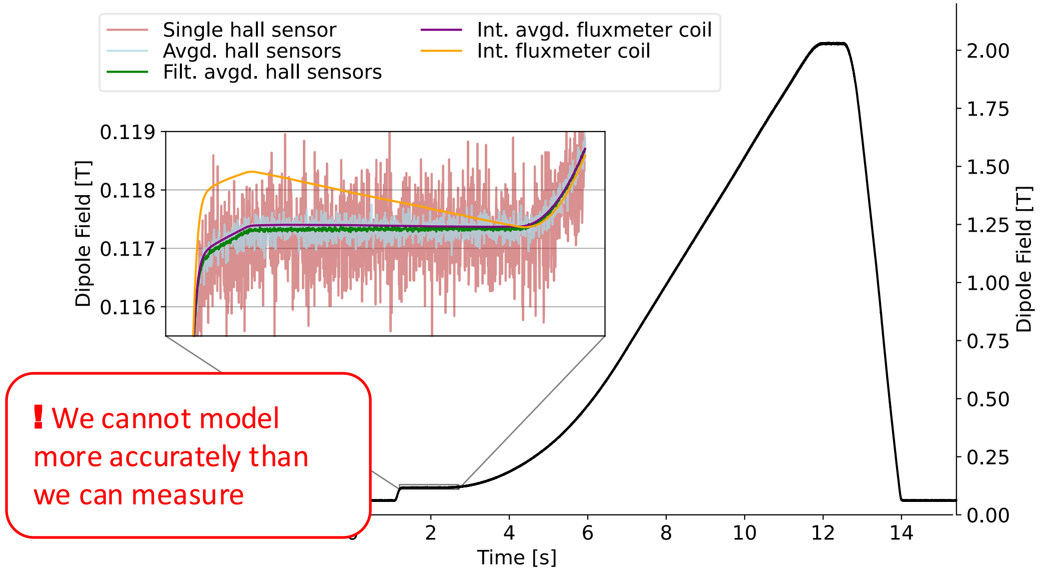
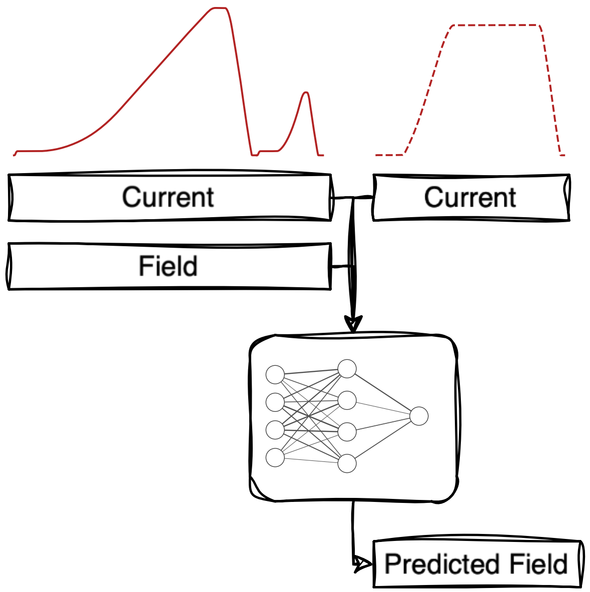


Field prediction

High-Accuracy Field Modeling Techniques

- Model measured $\{I, B\} \rightarrow B$ as a multivariate time series
  - $1 \times 10^{-5}\,T$ (10 ppm) accurate field predictions using (NN) transformers, learning from **only data**
  - Variables used for training restricted to what is available online



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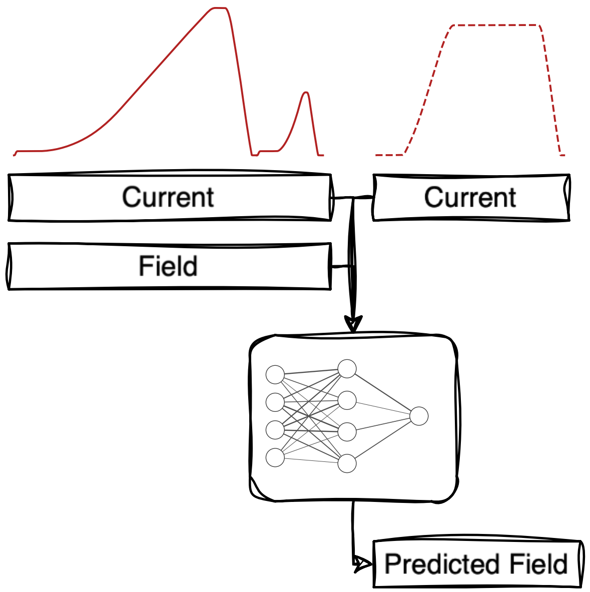
  - Autoregressive predictions the only choice for MQ+



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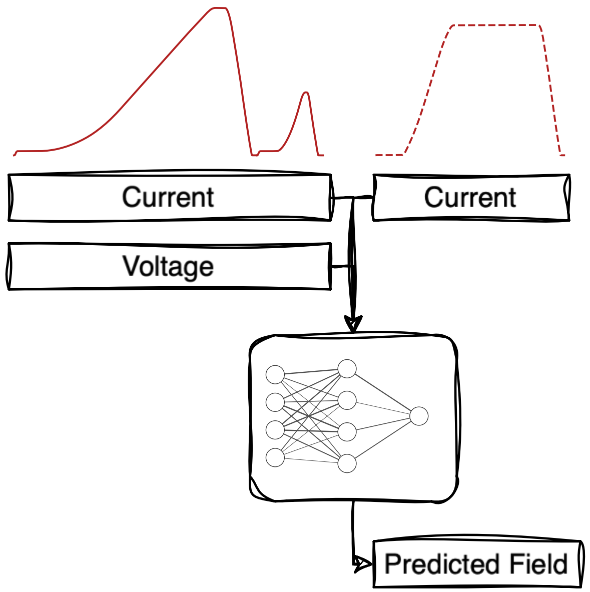

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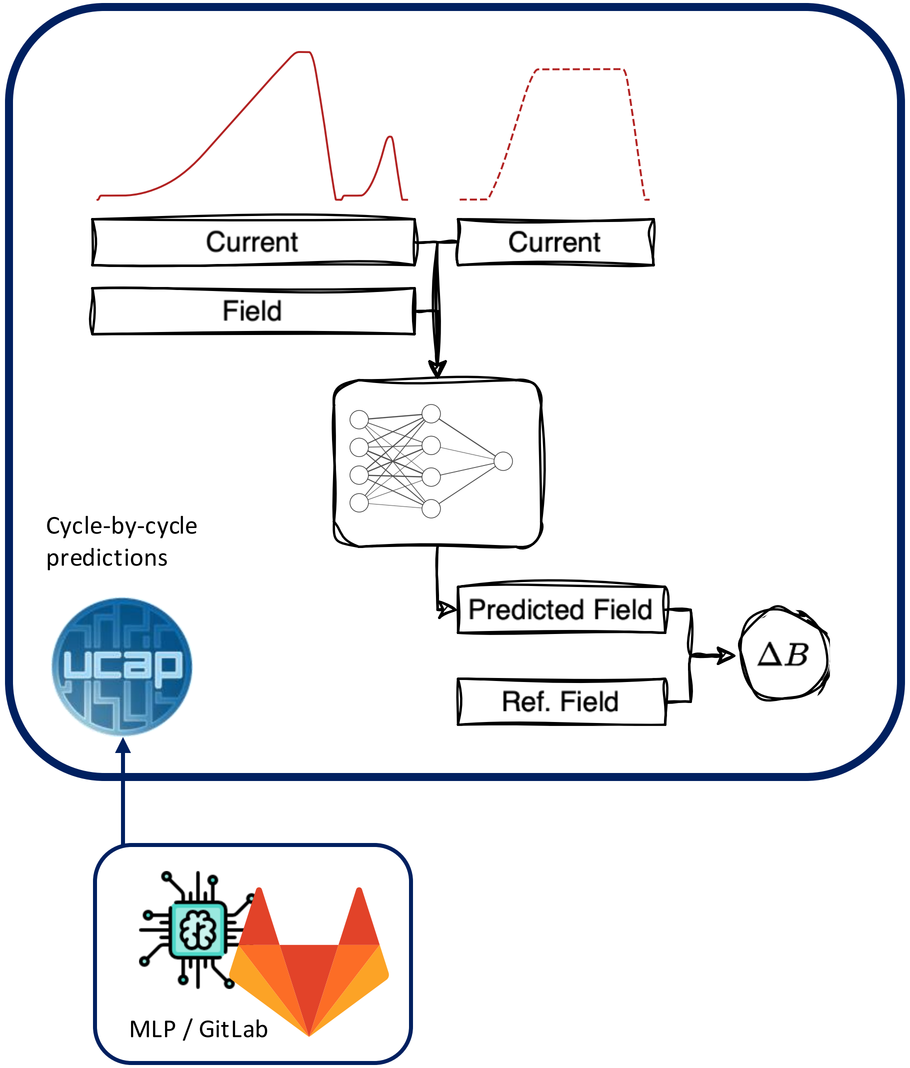
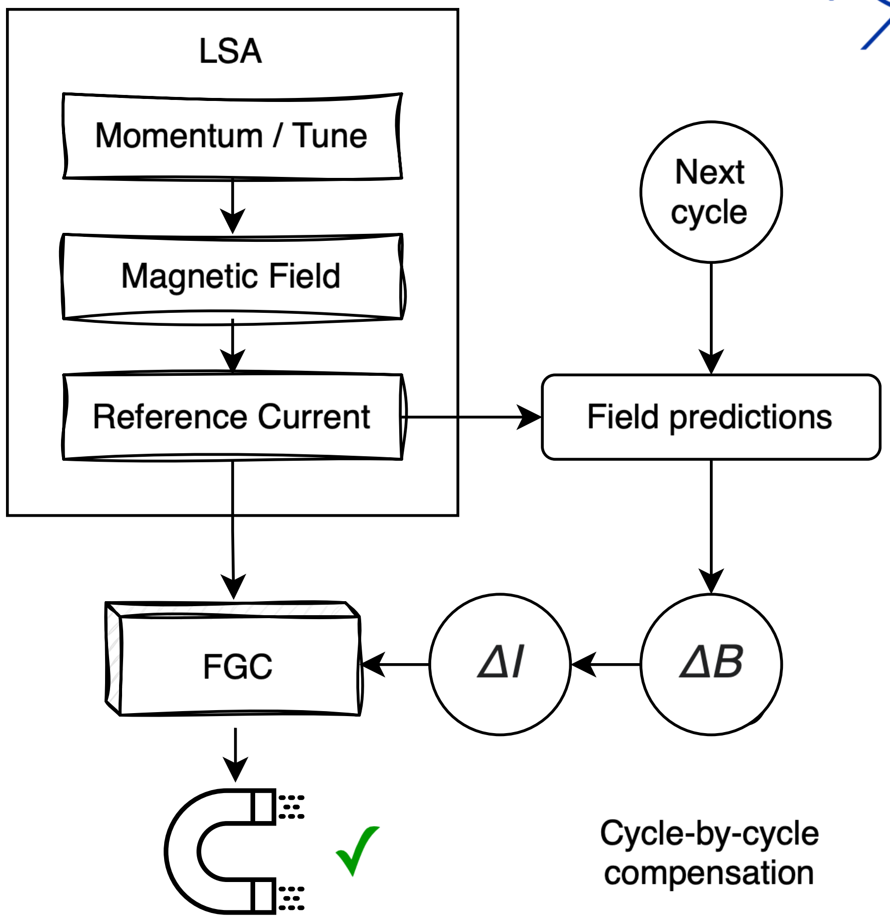


Feed-forward control strategy

Vertical integration of control stack

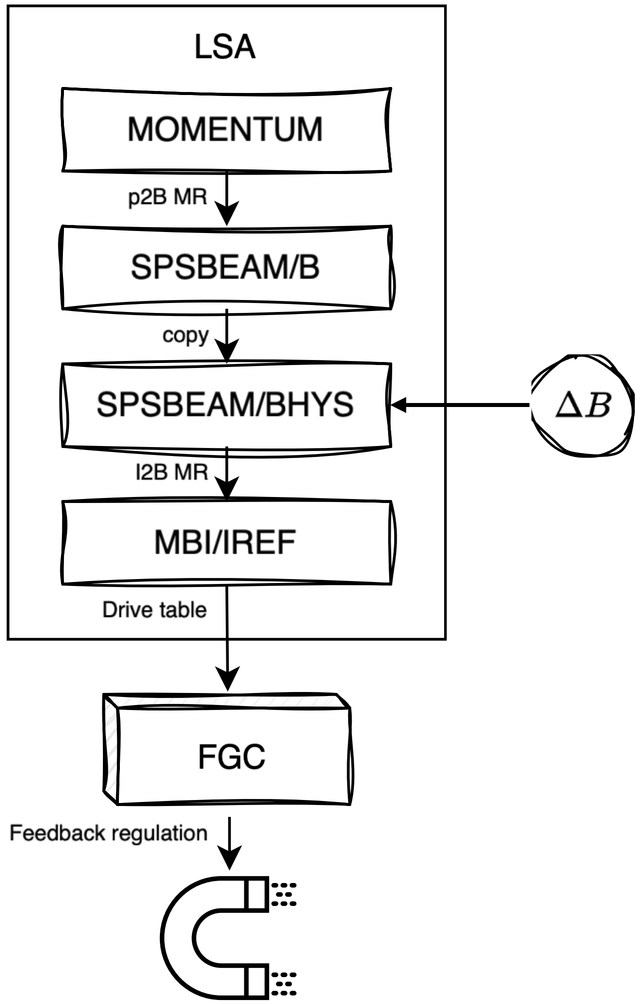


Feed-forward control strategy

Vertical integration of control stack

- New ΔB (ΔI) to to be applied **every cycle *before* cycle start**

- Now: trim LSA parameter
  - Leverage LSA to figure out ΔI and drive to FGC



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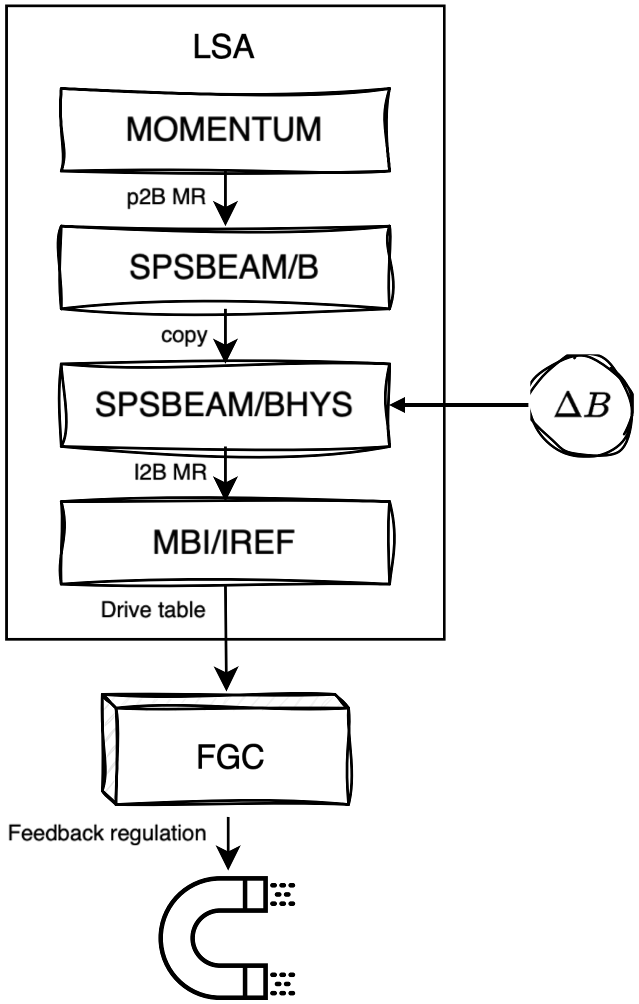

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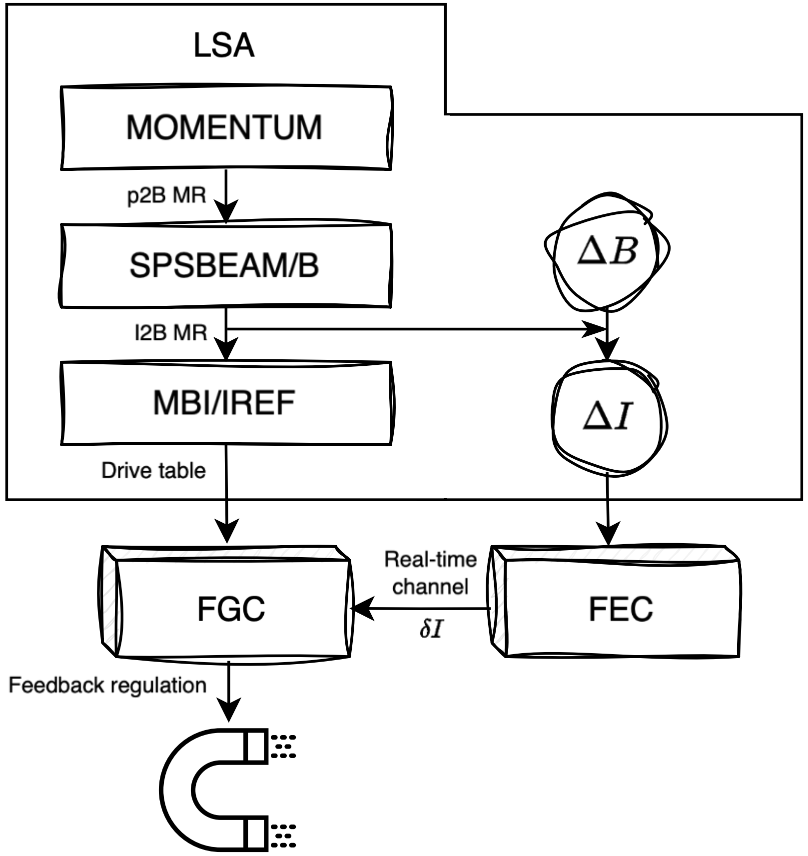
- Future: use FGC real-time channel to pass ΔI
  - … but still use LSA to translate $\Delta B \rightarrow \Delta I$
  - One step closer to “real-time” field compensation



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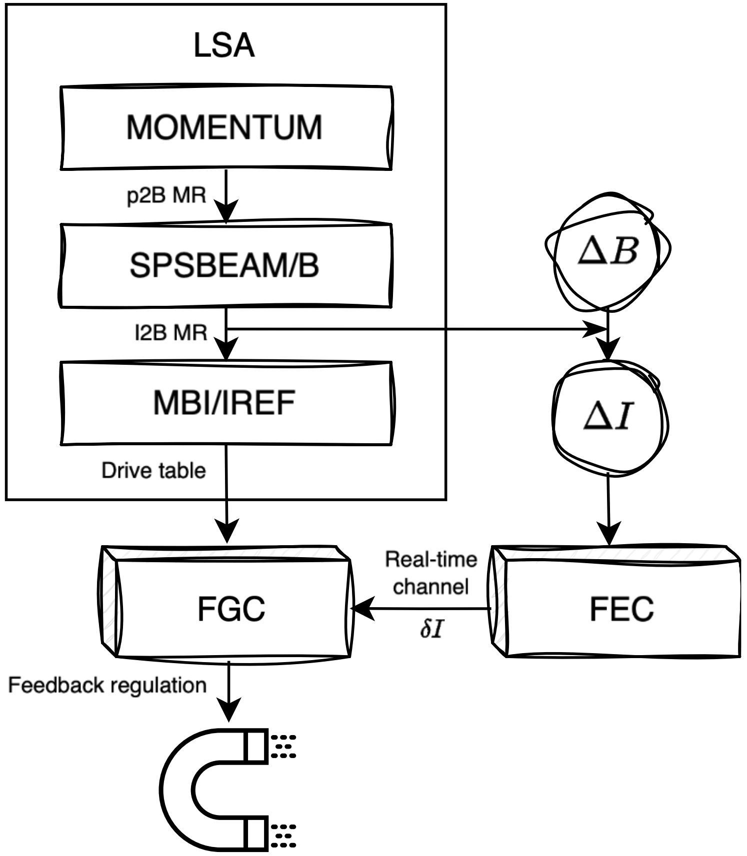
  - One step closer to “real-time” field compensation
- Future-future: bypass LSA entirely
  - Autonomous background field compensation

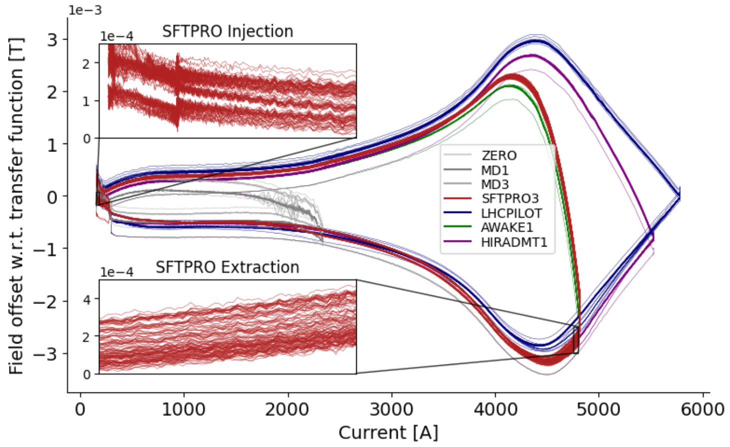


Controlling the AI

Going towards full automation

- Limiting compensation range
  - Hysteresis effects ± 1 permil, but cycle-to-cycle differences are $\pm$ 100 ppm or less
  - $\Rightarrow$ We can bound compensation ranges to safe (and known) limits

SPS MBI Cycle-to-cycle hysteresis



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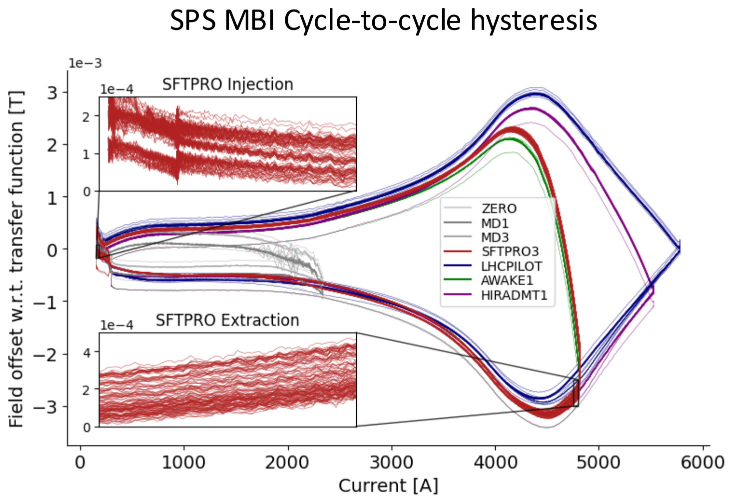
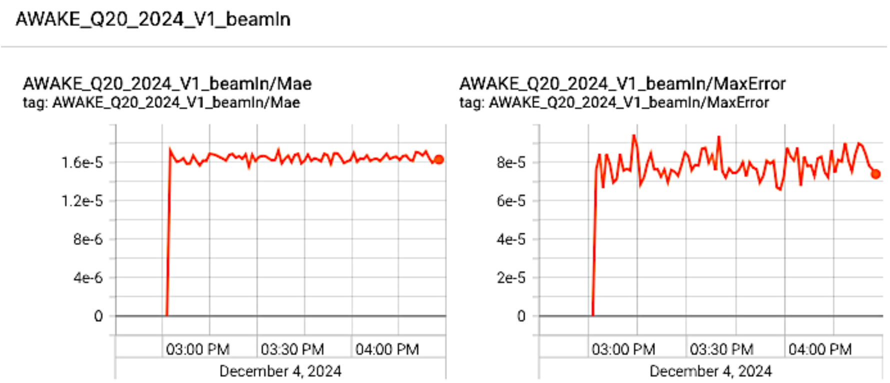
  - $\Rightarrow$ We can bound compensation ranges to safe (and known) limits
- Significant testing before "hands-free" deployment
  - We guarantee monitoring of field predictions and compensation
  - Set up metrics to monitor online field prediction quality
    $\Rightarrow$ stop compensation when metrics go beyond limits
  - Different metrics needed for MQ+ where B-Train is not available
  - Monitor autoregressive prediction drift over time
    - Can be solved by modeling $\{I, V\} \rightarrow B$





New magnetic measurement / magnetic preparation paradigm

Lessons learned – for the future

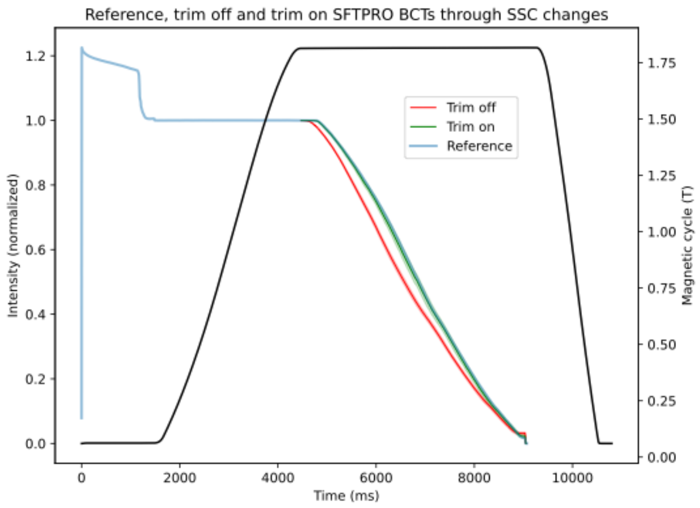
- High-accuracy measurements of physics cycles I_{ref} are not plug-and-play
  - New measurement bench and sensor fusion developed for MBI/MQ/LOD/LSF to reach B-train level accuracy ($\approx 1 \times 10^{-5}$ T / 10 ppm)
  - Standard characterization of SPS magnets are qualified comparing with reference magnets for the absolute field (at 10^{-5} level) in the lab. Work on going to improve for AI training requirements specially for dynamic effects study.
- Physical constraints are also a concern
  - To accurately represent the machine, measurements with a vacuum chamber may be necessary, depending on the measured effects magnitude; dipoles already measured with a vacuum chambers, for MQs a new fluxmeter is designed and produced.
  - In few cases (e.g., LEIR) spare magnets not available for measurement / characterization on demand
  - Magnets not always available for measurement / characterization on demand; crucial to have flexible laboratory
- Powering limitations in lab
  - Power converters stability and control algorithms overtime (I_{meas} lab vs machine) may lead in a different response for the same programmed current (I_{ref}).
  - The measurements in the laboratory may have a different data distribution w.r.t. data from real-time measurement system, not necessarily compatible for ML training purpose

! We cannot model more accurately than we can measure

Operational status of hysteresis compensation

Summary

- < 100 ppm field corrections for SFT flat top to stabilize the spill macrostructure
  - To be put into operation and significantly tested and monitored by mid-2025
- ≈ 10 ppm accurate field predictions for common cycle sequences
  - … and ≈ 100 ppm predictions on more general cycle sequences
  - Pre-train NN models on simulated data and transfer-learn to measurements
  - Low-field correction at injection to reduce injection losses within reach

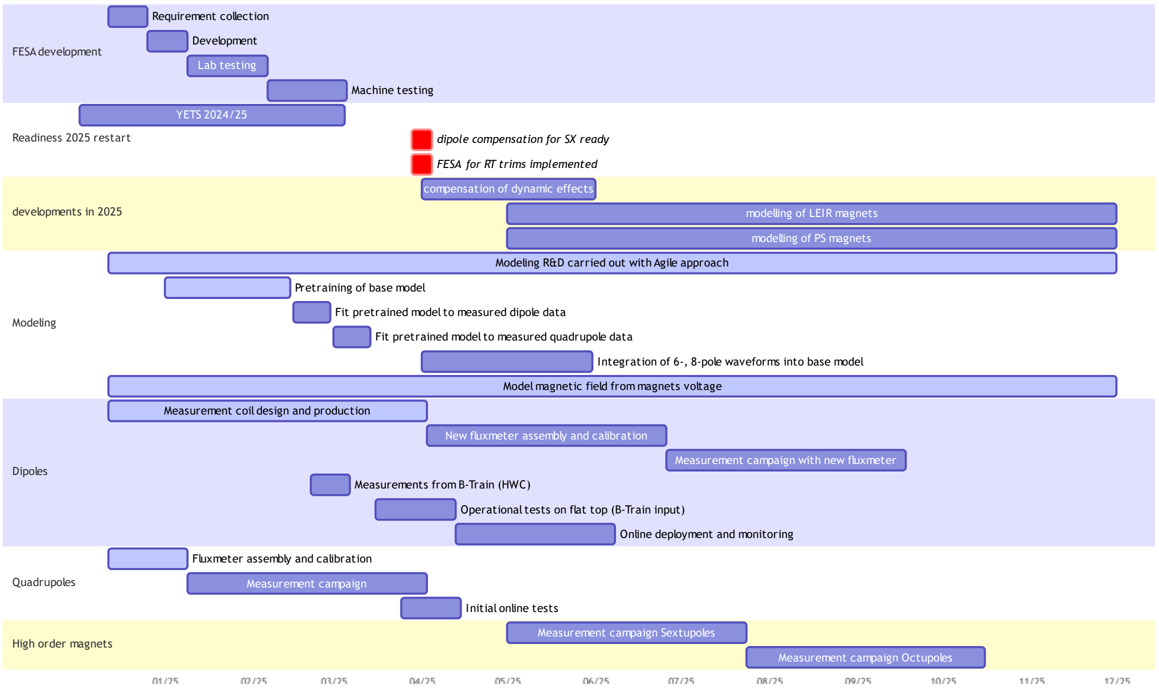


- But not all phenomenon can be measured
  - Beam-based eddy-current studies and/+ ML-field compensation at flat bottom and ramp by mid-2025
  - MD1 quasi-degaussing can go out the window after full field compensation
- Feed-forward compensation scheme has proven benefits
  - Minimally invasive to the machine, and transparent integration into control stack
  - Compensation strategy is modular and highly flexible – and **extendable to other magnets and machines**

EPA WP4 in 2025

Summary and Outlook

- SPS MB full-cycle compensation
- SPS other magnets field compensation
  - Initial tests of MQ field compensation from beam commissioning 2025 and through the year
  - … and sextupole and octupole field compensation tests to follow after MQ



- Towards other machines
  - Soon™ QUEST in BE-ABP for simulating LEIR dipole and PS combined function magnets
  - Field compensation for other machines during LS3 following SPS
    - Pulsed magnetic measurement procedures learnt from SPS experiences in lab critical for success

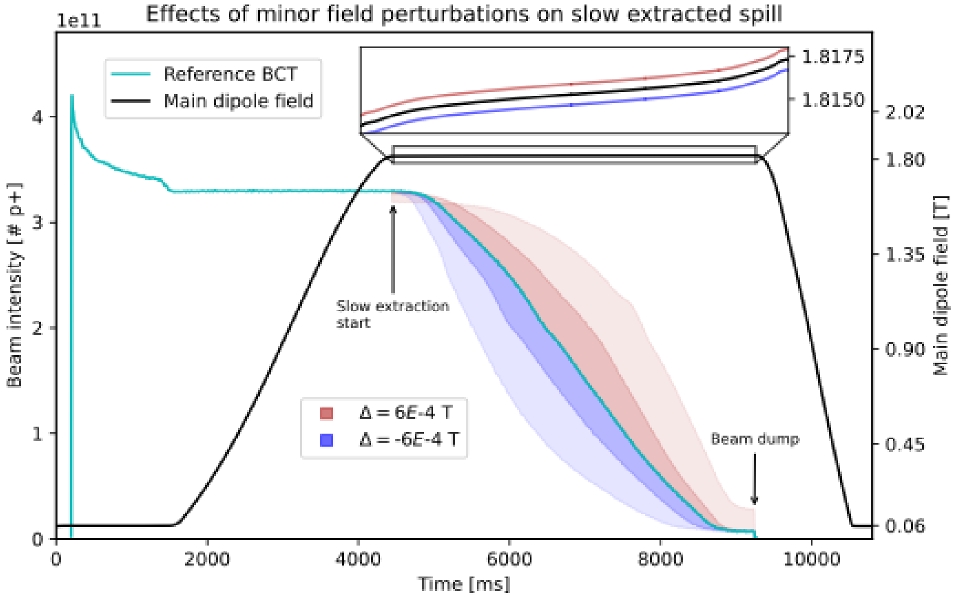
Questions

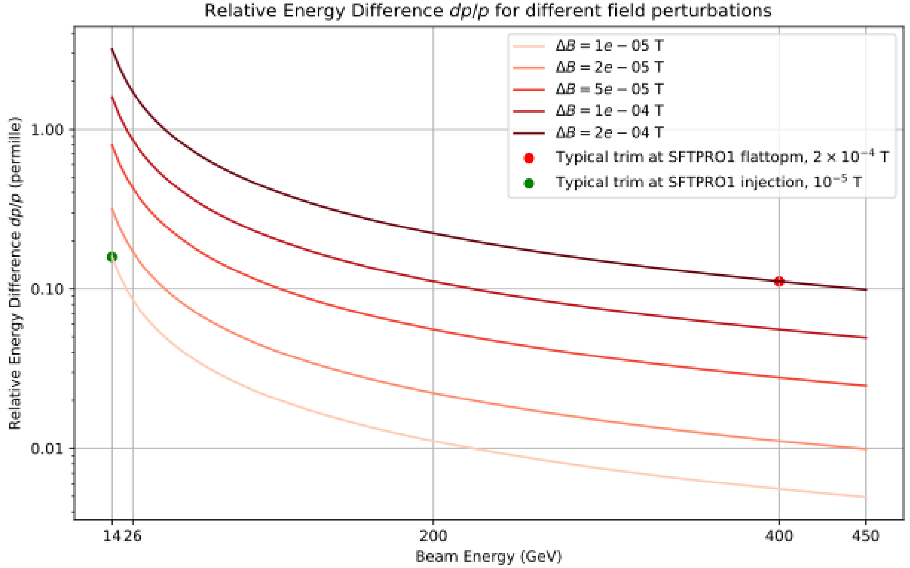
Extra slides

Analysis – Hysteresis in SPS main dipoles

Overview

- Field deviations due to hysteresis between $\pm 3 \times 10^{-3}$ T at most
  - But typically, below $3 \times 10^{-4}\ T$ cycle-to-cycle
  - Similar range for SPS QF/QD
- The field corrections depend on beam energy / field strength / tolerance
  - For SFTPRO slow extraction (400 Gev), tolerance is below 1×10^{-4} T
  - For SFTPRO injection (14 GeV) tolerance is $\approx 1 \times 10^{-5}$ T
  - For LHC-type injection (26 GeV) tolerance is $\approx 2 \times 10^{-5}$ T

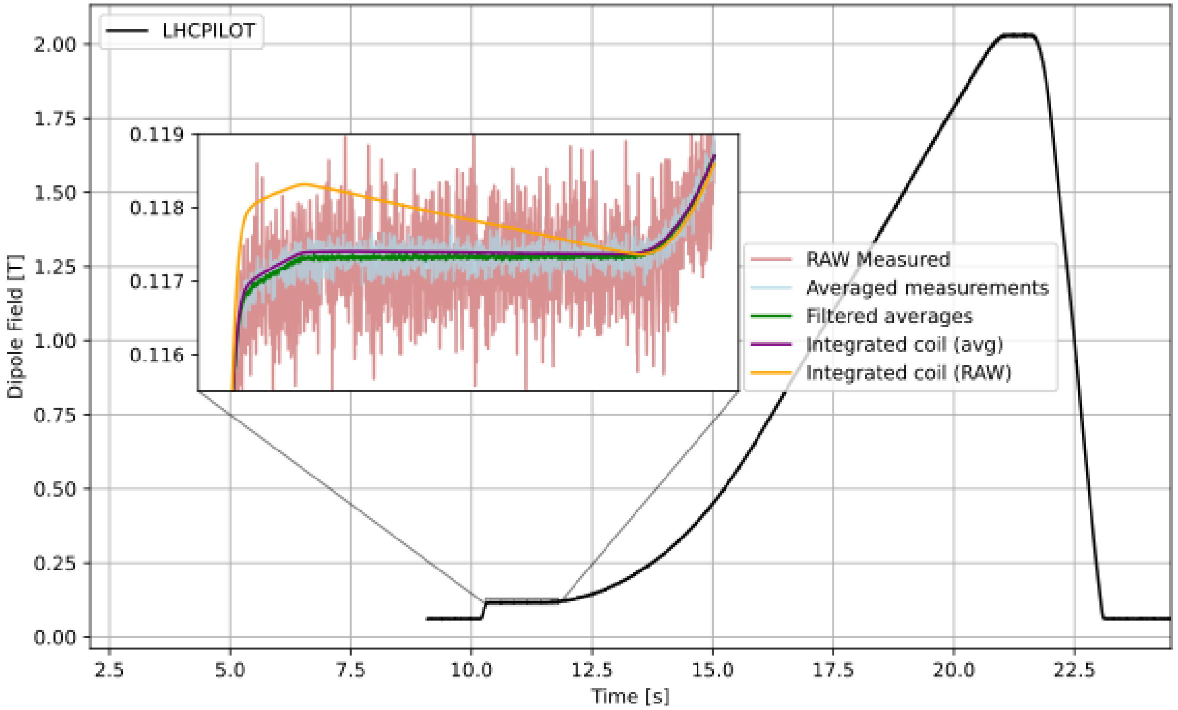




Magnetic measurements

Know

- Measure dipole magnetic response with online B-train
  - Problems with drift to reach desired accuracy, especially at SFTPRO FB
- Lab measurements for quadrupoles, sextupoles, octupules
  - Challenges to reach desired accuracy using induction coil (drift) or hall sensors (noise)
- Accurate pulsed measurements very challenging in the lab
- Power converter in lab is different from FGC
  - Lab not entirely representative of SPS conditions

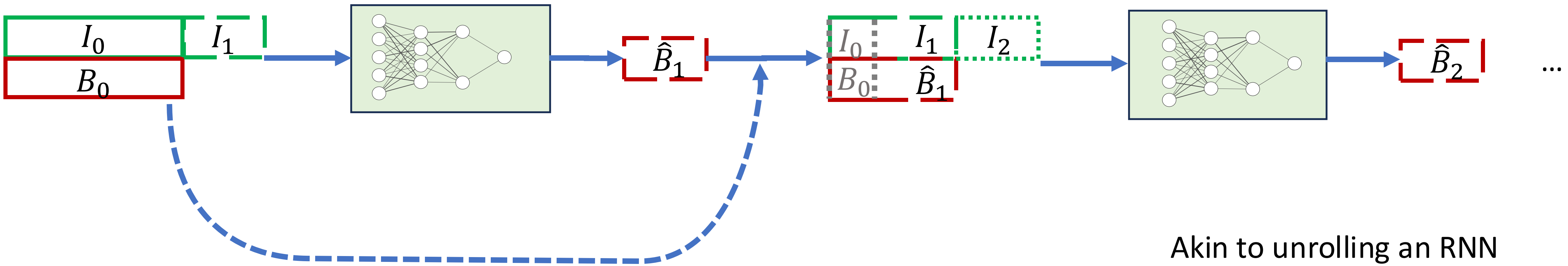


Autoregressive predictions

Predict

- With initial I_0, B_0 of length c and I_1 of length p, predict $\hat{B}_1$
- For next step use I_1 and $\hat{B}_1$ (and part of I_0 and B_0 if $p < c$) to predict $\hat{B}_2$

- We only need to known ground truth field B_0 at beginning of prediction, the rest are prediction only
  - Since for QF/QD+ we do not have ground truth observable (B-Train)

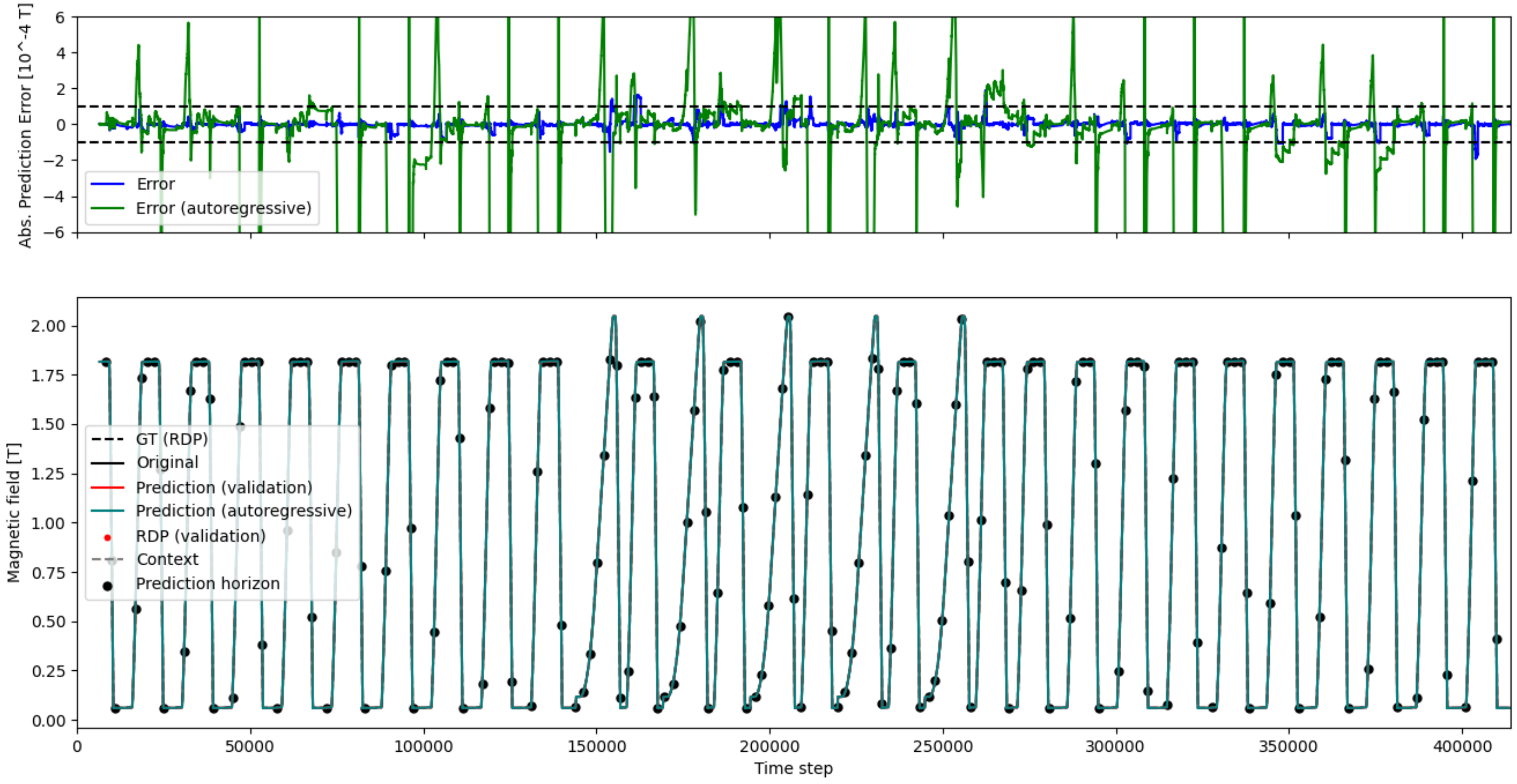


Akin to unrolling an RNN

Validation

Predict

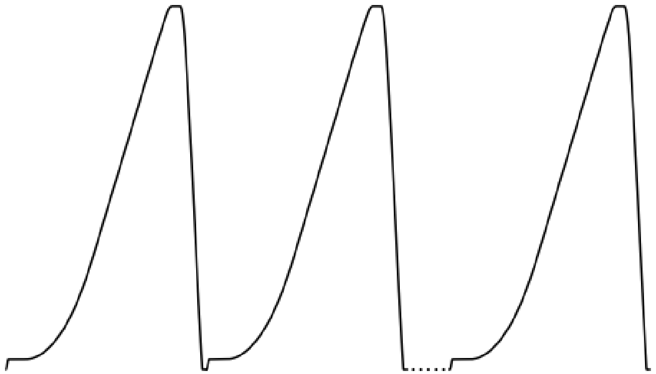
- Validation on common supercycle show promising results
  - Below 10^{-4} T error in most cases
  - Error does not seem to run away / accumulate when predicting autoregressively



Cycle-by-Cycle Online inference

Predict

- Precycle the magnets to always start from the same field
  - For SPS MBIs: I_0, B_0 from B-Train
  - For the rest: I_0, B_0 from lab
- Then predict magnetic field for each cycle
  - 2500 ms before cycle start, predict $\hat{B}_{n+1}$ using programmed current I_{n+1}^{prog} and I_n, B_n for the next cycle
  - N.B. for magnets with B-train we can always use “true” past for future predictions



Precycle

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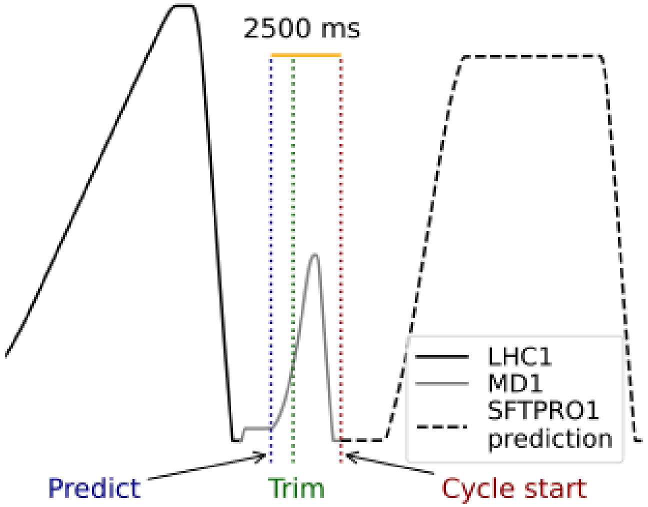
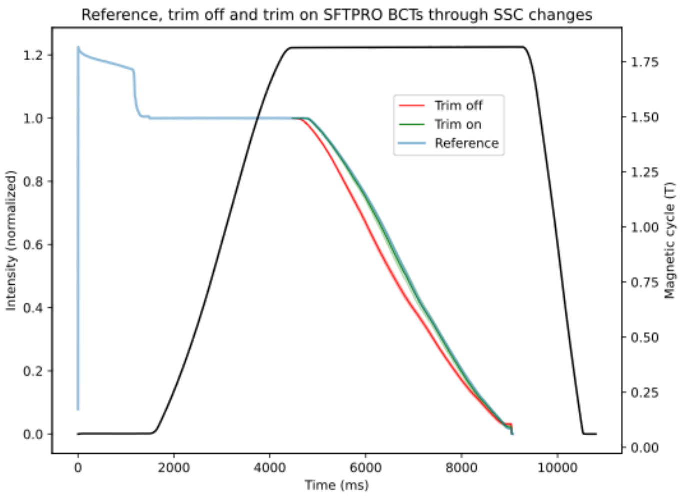
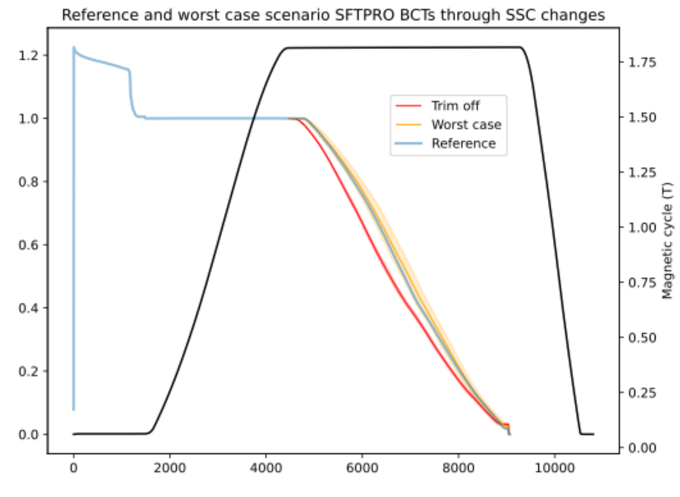


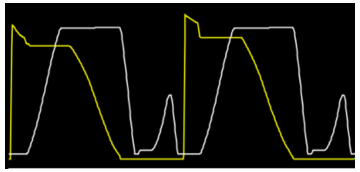
Significant and consistent improvements on spill quality

Results

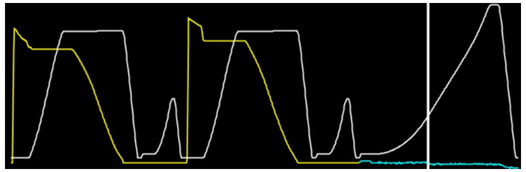
- Spill macrostructure stable in most cases
  - Worst case is still better than when hysteresis compensation is off and switching from FT → LHC+FT SSC
  - Most cases preserves spill macrostructure through supercycle changes, or when there are 1+ FT in the same supercycle







(Field compensation OFF)
FT + LHC -> 2x FT



Field compensation ON – worst case

Significant and consistent improvements on spill quality

Results

- Evolution of spill quality over time, with autoregressive field predictions + compensation
  - Corrections only on SFTPRO1 flat top, on **every cycle**
- Reference taken at the beginning and unchanged throughout the MD
  - Spill duty factor remains largely unchanged
  - … But RMSE between reference and measured BCT is significant when field is poorly / uncorrected